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A novel ion cooling trap for multi-reflection time-of-flight mass spectrograph

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A B S T R A C T

A radiofrequency quadrupole ion trap system for use with a multi-reflection time-of-flight mass spectrograph (MRTOF) for short-lived nuclei has been developed. The trap system consists of two different parts, an asymmetric taper trap and a flat trap. The ions are cooled to a sufficient small bunch for precise mass measurement with MRTOF in only 2 ms cooling time in the flat trap, then orthogonally ejected to the MRTOF for mass analysis. A trapping efficiency of ≈27% for $^{23}Na^{+}$ and ≈5.1% for $^{7}Li^{+}$ has been achieved.

1. Introduction

Precision mass measurements of exotic nuclei with a multi-reflection time-of-flight mass spectrograph (MRTOF) will be key experiments at the SLOWRI facility at RIKEN [1–4]. The MRTOF is expected to be one of the most powerful mass measurement devices, competitive with standard Penning trap mass spectrometer (PTMS) [5]. In the experiments for exotic nuclei, the advantages of the MRTOF over the standard PTMS are shorter measurement times for medium and heavy masses, and reduced yield requirements as all detected ions contribute equally to the statistics. These features will allow us to measure, for instance, masses related to r-process nucleosynthesis [6] as well as superheavy elements with short life-times ($T_{1/2} \lesssim 100$ ms) and low production yields.

The MRTOF is coupled with a gas cell to decelerate and thermalize high-energy radioactive ions; a multipole ion guide system transports the extracted low-energy ion beam to the MRTOF [7]. As MRTOF mass measurements are based on time-of-flight (ToF) measurement, the continuous beam extracted from the gas cell must be converted into a pulsed beam. An optimal time-of-flight measurement would feature an extremely long flight path traversed by ions with a short-duration time-structure and well-defined energy. For this purpose, a novel ion cooling trap system, specialized for rapid cooling and creation of ion pulses with excellent optical properties, has been developed. We have characterized the trapping efficiency of the trap system with several figures of merit and found it to be very well-suited for the MRTOF.

2. Trap system

In order to convert the continuous beam delivered from the gas cell, a buffer gas filled ion trap must be used. The use of gas-filled radiofrequency multipole ion traps to accumulate and cool ions is a proven technique [8]. Our trap system is located at the end of the transport line from the gas cell, just prior to the MRTOF. It consists of a "taper trap" and a novel "flat trap". Owing to the flat trap geometry, ions can easily be accumulated from both directions and ejected orthogonally.

The taper trap illustrated in Fig. 1 consists of four tilted rods with radius of $r = 5$ mm and length of $L = 190$ mm. The inter-rod-gap radius r_0 at the outer end is 4.35 mm, while at the inner end it is slightly larger, $r_0 + \Delta r_0$, due to the tapered structure. The optimal Δr_0 was chosen based on SIMION [10] simulations.

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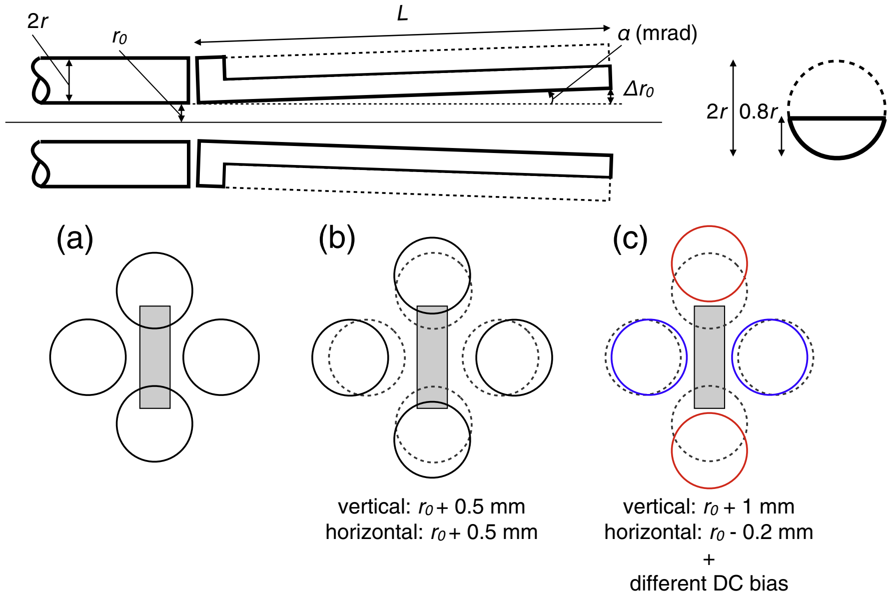
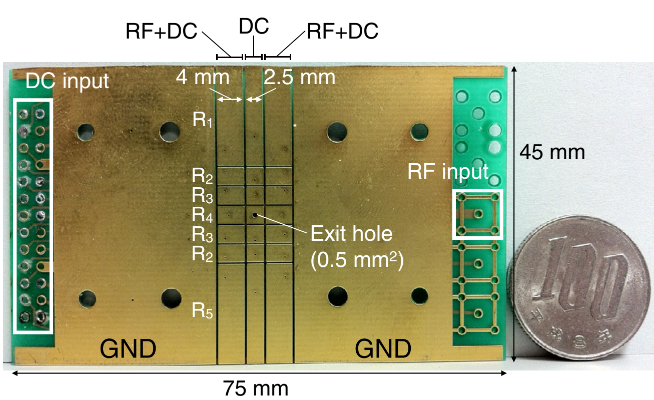


Fig. 1. (Top) Schematic view of the taper trap. In order to fit into the stainless tube, the rods are 4 mm thick circular segments. (bottom) Cross sectional view of the rods in three configurations: (a) the parallel trap, (b) the taper trap and (c) the asymmetric taper trap (see text). The cross sectional view of entrance side is indicated by dashed line and the flat trap aperture is indicated by rectangular gray area in bottom figures. The rods are mounted in PEEK blocks at each end.



Electrode		R_1	R_2	R_3	R_4	R_5
Length (mm)		14.9	2.6	2.6	2.6	14.9
DC voltage (V)	: Accumulation*	-4.5	-5.7	-5.8	-6.0	5.0
	: Cooling	27	10.5	7.5	5.0	27

* R_1 side is the entrance in this case.

Fig. 2. . Photograph of the flat trap PCB with scales and typical DC voltages annotated. Capacitors and resistors on the back of the PCB distribute RF and DC signals to the individual electrodes. Spacing between adjacent electrodes is 0.3 mm. A ¥100 coin is included for scale.

This tapered structure can produce an effective axial drag force [9] without the usual need for segmentation of the rods. The taper trap is housed in a stainless steel tube to isolate it from the vacuum region outside the flat trap; a collimator at the entrance reduces the gas flow into the vacuum region. The flat trap is constructed using two printed circuit boards (PCB) as shown in Fig. 2. It operates on the same principle as a traditional segmented Paul trap, but uses a novel geometry. While a traditional Paul trap creates a well-approximated quadrupole field using four rod electrodes, our flat trap design uses six strip electrodes. While the quadrupole approximation is not sufficient for use as a mass filter, it is perfectly well-suited for ion storage and cooling.

The PCBs are mounted on an aluminum block and separated by 4 mm distance. Each PCB consists of three strips divided into 7 segments (see Fig. 2). The central electrode of each board has a 0.5 mm^2 plated hole at its center. By applying a potential difference between the center electrodes of the PCBs, ions can be extracted orthogonally to the injection axis through the small exit holes. DC electric potentials are used, in the standard manner, to create an axial potential well while an RF signal superimposed on the outer strips provides a radially confining pseudo-potential. By operating the trap in RF unbalanced mode, there is no need to connect the central strip segments to an RC network, a feature which allows for very fast switching of the centermost segment. Such fast switching is used to apply a well-defined dipole field at the trap center to eject ions from the trap via the small hole in the central electrode. This ensures that the ion optical properties of the ion pulse are without higher-order optical aberrations and that the ions have a low emittance.

3. Results and discussion

The performance of the trap system was investigated in terms of the trapping efficiency, cooling time and trap capacity. Alkali ion sources are capable of providing K and mono-isotopic ^{23}Na and ^{7}Li ions. $^{7}Li^{+}$ and $^{23}Na^{+}$ were used for the efficiency measurements, while K^{+} ions were used for cooling time and capacity measurements.

3.1. Trapping in the taper trap

In a buffer-gas filled trap, cooled ions don't come out efficiently and quickly without any drag force. As previously mentioned, a taper structure produces an effective axial drag force. Due to the drag force, the pre-cooled ions can be efficiently transported to the flat trap. The axial drag force of the taper trap is determined by the rod angle, α. The value of α was optimized using SIMION. Simulation showed an increase in transmission with larger angles. The effective acceptance of the flat trap, however, is estimated to be about 2.8 mm ($\approx$70% of the PCB gap). An angle of $\alpha = 2.6$ mrad, corresponding to $\Delta r_0 = 0.5$ mm for $L = 190$ mm was thus adopted [11].

Using this geometry, the trapping efficiency and effective drag force of the taper trap were studied. The experimental setup is